TECHNICAL NOTES.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No.17.

# ITALIAN AND FRENCH EXPERIMENTS ON WIND TUNNELS.

By

Wm. Knight, Technical Assistant in Europe,
Paris Office, N.A.C.A.

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The National Advisory Committee for Aeronautics submits the following report, which is the result of a special analysis of the measurements and the investigations of various models of wind tunnels in Europe, made by Mr. William Knight, now Technical Assistant in Europe to the National Advisory Committee for Aeronautics. This report was presented by Mr. Knight in 1918 to Dr. W. F. Durand, then Scientific Attaché to the American Embassy, Paris, France.

## Costanzi's Experiments.

The experiments made by Eiffel in his laboratory at Auteuil in the aerodynamical tunnel designed by him induced Colonel Costanzi of the Italian Army to start two series of experiments at the "Instituto Centrale Aeronautico" at Rome, with a view of determining:

1st - What was the influence of the surrounding building in which the tunnel was installed on the efficiency of the installation, and

2nd - How the efficiency of the installation was affected by the design of the tunnel.

The models of tunnels used both in the first and in the second series of experiments were made out of a cylindrical chamber connected at one end to a nozzle and at the other end to a diffuser, the shape and dimensions being as shown in Fig. 1.

A 24 blade air-screw driven by a 2 HP D.C. electric motor supplied the air current, the velocity of which was measured in every case in the cylindrical chamber with a Krell anemometer. A dynamometer inserted in the axis of rotation between the motor and the air-screw measured the torque absorbed by the propeller for any corresponding velocity of the air current as registered by the anemometer. The speed of the motor varied between 250 and 3200 R.P.M. Colonel Costanzi in "Rendiconti delle esperienze e degli studi eseguiti nello stabilimento di Experienze e Costruzioni Aeronautiche del Genio - Fasc. 3° Vol. II" gives the velocity of the air in the restricted section of the tunnel in meters per second for each experiment performed, the speed of the motor in r.p.m. and the power absorbed by the dynamometer in kilogrammeters. The results are presented in 21 Tables (one for each experiment performed) and 6 diagrams.

In order to facilitate the comparison of the results obtained, I have arranged differently the experimental data presented by Colonel Costanzi. Instead of giving the work absorbed by the dynamometer, the ratio $\frac{P_u}{P_m} = \rho_t$ was calculated in every case.

$P_u$ is the energy possessed by the air in the restricted section of the tunnel where the velocity is measured.

$$P_u = \frac{M_v^2}{2}$$

where:

$$M = \frac{\pi d^2}{4} \times v^3 \times \frac{\delta}{2g}$$

d = diameter of tunnel where the air velocity is measured.

v = velocity of the air in the section of the tunnel having a diameter d.

$\delta$ = density of the air at 15° temp. and 30" barometric pressure.

g = acceleration due to gravity.

$P_m$ is the technical energy absorbed by the dynamometer for producing an air current of the velocity $\underline{V}$ in the section $\underline{d}$ of the tunnel and is expressed in the same units as $P_u$.

$\rho_t = \frac{P_u}{P_m}$ is the efficiency of the installation.

In Tables I and II are given the values of $\rho_t$ calculated for the 24 groups of experiments performed by Colonel Costanzi.

In Table I are tabulated the results of the first series of 11 experiments made for determining the influence of the surrounding building on the mechanical efficiency of an aerodynamical tunnel open at both ends. For these experiments, two models of tunnels having the dimensions shown in Fig. 1 were used. The models were made out of wood polished inside so as to reduce as much as possible the windage losses, and were inclosed in a model building of the dimensions given in Fig. 1.

Three different models of buildings were used for these experiments and they were all made with the end doors and the roof removable, so as to allow the measurement of the power absorbed by the dynamometer for producing an air current of a desired velocity, when the intake and outlet of the air was taking place either into the closed atmosphere of the building or into the open air. A removable diaphragm could be placed inside of building No. 1 normal to the axis of the tunnel, all around the restricted section where the air velocity was measured. This diaphragm when it was in place prevented the circulation of the air from one end to the other inside of the building.

In Table II are given the values of $\rho_t$ for 13 groups of experiments made for determining the influence of the design of the nozzle and the diffuser and the location of the air-screw on the efficiency of the installation. In Fig. 2 are given the dimensions of the models experimented upon in each case.

The conclusion to be drawn from the first series of experiments are:

1. If the roof and the doors of the building are closed, the values of $\rho_t$ as obtained under these conditions are about one half of the corresponding values of $\rho_b$ as obtained with the end doors open (see experiments Nos. 1 and 4).

2. The opening of either the inlet door or the outlet door, the addition of a diaphragm in the middle of the hall all around the tunnel, such as to prevent the air from circulating from an end to the other inside of the building, the opening of the roof, and the increase in size of the building, have no appreciable influence on the values of $\rho_t$, which will be only slightly larger than when the doors are closed and the roof is in place.

3. The efficiency of a tunnel having the nozzle and the diffuser made out of parabolic surfaces is about one half the efficiency of a tunnel of equal dimensions with straight conical inlet and outlet, operating under the same conditions.

The conclusions that can be drawn from the second series of experiments are:

1. The extension of the diffuser back of the air-screw increases the values of $\rho_t$.

2. If the diffuser is entirely taken off, the efficiency of the installation is practically equal to the efficiency of $\rho_t$ the air-screw.

3. A cylindrical extension of the diffuser right back of the air-screw has the tendency to decrease the value of $\rho_t$

4. If both the nozzle and the diffuser are connected at the smaller end to a cylindrical chamber having a diameter double the smallest diameter of the nozzle and the diffuser, the value of $\rho_t$ is about 40% smaller than if the diameters were the same (see experiments 22 and 24).

5. A slight discontinuity over the length of the experimental chamber (cylindrical portion of the tunnel) decreases only slightly the value of $\rho_t$ (see experiments 23 and 24).

6. The increase of the ratio of the diameters at the outlet and at the inlet of the diffuser from 1.7 to 4.2 produces a decrease of $\rho_t$ of about 60% (see experiments 16 and 21).

## Castellazzi's Experiments.

A third series of experiments was performed later on by Lieut. Castellazzi of the Italian Army (see "Rendiconti dell' Istituto Centrale Aeronautico, Anno VII, 1917") for determining the most efficient design of a tunnel of the Crocco type. In Fig. 3 are given the dimensions of six models of tunnels on which seven series of experiments were performed. Also in this case I have calculated the values of $\rho_t$ for each corresponding velocity of the air in the experimental chamber, 14-3/16" diameter, and the values obtained are tabulated in Table III.

The conclusions that can be drawn from these experiments are:

1. The extension of the diffuser behind the air-screw produces an increase of $\rho_t$.

2. A decrease in length of the cylindrical chamber increases the value of $\rho_t$.

3. The shape of the section of the ducts for the return of the air has no appreciable influence on the value of $\rho_t$.

4. A slight interruption over the length of the experimental chamber decreases only slightly the value of $\rho_t$.

5. The opening of the door on "a" communicating to the outside produces a large drop in the value of $\rho_t$.

Comparing the results obtained from Costanzi's experiments and the results of Castellazzi's experiments we may conclude that:

1. The efficiency of a tunnel of the Crocco type is larger than the efficiency of an Eiffel tunnel of the same dimensions (see Costanzi No. 21 and Castellazzi No. 1). The efficiency of the Eiffel tunnel at Auteuil at a maximum wind speed of 104 feet per second is $\rho_t = 1,37$ and the power needed is 84.5 HP; while the efficiency of the Crocco tunnel at Rome at a maximum wind speed of 165 feet per second is $\rho_t = 2.9$ and the power absorbed is 113 HP. At a wind speed of 104 feet per second the Crocco tunnel gives $\rho_t = 2.65$ and the corresponding horse power supplied by the motor is only 28 HP.

2. A tunnel of the Crocco type has the great advantage of making possible its installation in a small building, the dimensions of the

building having no influence at all on the value of $\rho_t$, which, in the case of an Eiffel tunnel, is greatly influenced by the sides of the surrounding building. Another advantage of the Crocco tunnel is to be found in the possibility of controlling the temperature and the humidity of the air and in the elimination of the disturbing action of the wind at the entrance of the nozzle and at the outlet of the diffuser.

Model No. 4 of Castellazzi's experiments was adopted for the installation of the tunnel at the "Istituto Centrale Aeronautico, Roma." Another series of experiments was started next for determining the number and the width of blades of the air-screw which would give the best results. In the final installation of the "Istituto Centrale" eight propellers, 23-5/8" diameter, were tested in tunnel No. 4. In Table No. VII are given the values of $\rho_t$ calculated in the same way as before and the r.p.m. of the driving motor for every corresponding wind velocity in the section 14-1/8" diameter, are also given. For the final installation, a N.P.L. type of propeller with seventeen blades was adopted. In Fig. No. 4 are shown the main dimensions of that installation, and in Table No. IV are tabulated the motor horse-power and the r.p.m. for corresponding velocities of the air in the cylindrical chamber, as obtained from test.

The efficiency of the propeller was calculated by measuring the air pressure right in front and immediately behind the propeller. No details are given in the publication of the test results about the arrangement adopted for measuring exactly these pressures. The values given for the efficiency of the propeller seem to be too large. The values of $\rho_t$ were calculated also in this case and, in addition, the values of $\rho_b$ are given in the last column of Table IV. ( $\rho_b = \frac{\rho_t}{\rho_v}$ , where $\rho_v$ is the efficiency of the air-screw.)

## Eiffel's Experiments.

Recently another series of experiments was started by Eiffel in his laboratory at Auteuil on 34 models of tunnels of different dimensions as shown in Fig. 5.

The nozzle of each model was taking the air from the experimental chamber of the Eiffel installation where a depression of 51.5 millimeters of water was produced by starting the air-screw of the large tunnel. The depression H = 51.5 mm. at the nozzle of the model tested produced a current of air through the model of tunnel where the air depression h was measured at the cylindrical section. The efficiency of each model $\rho_b = \frac{h}{H}$ is given in Table V. Knowing h and $\rho_v$ I have calculated the velocity of the air in the cylindrical section of each model: $V = \sqrt{2ghd}$ where "d" is the ratio of the specific weight of the water used in the barometer on which h was measured and the specific weight of the air, and is: d = 800, giving V =

$\sqrt{2 \times 9.81 \times \rho_b \times .051, 5 \times 800}$; the values of V are tabulated in Table V.

This series of experiments was started by Eiffel in order to find out if, by changing the shape of the nozzle or of the diffuser of the large tunnel at Auteuil, the efficiency of the installation could be improved.

The conclusions arrived at by Eiffel are:

1. The largest value of $\rho_b$ with the models tested has been obtained with a nozzle at 35° and a diffuser at 7°, the largest diameter of both the nozzle and the diffuser being 3 times the diameter of the cylindrical chamber (see experiment No. 25, $\rho_b = 5.67$).

2. The largest value of $\rho_b$, when the largest diameter of both the nozzle and the diffuser is double the diameter of the cylindrical chamber, is obtained with a nozzle at either 35° or 22° and a diffuser at 7° (see experiments 1 and 17, $\rho_b = 4.08$).

3. If the largest diameter of the nozzle is 3 times the diameter of the cylindrical chamber, and the largest diameter of the diffuser is twice the diameter of the cylindrical chamber, the largest value of $\rho_b$ is obtained with a nozzle at 22° and a diffuser at 7° (see experiment No. 5, $\rho_b = 4.48$). If the angle of the nozzle is 35° instead of 22°, the value of $\rho_b$ does not change bg any appreciable amount (see experiment No. 24, $\rho_b = 4.38$).

At the Eiffel laboratory was also recently investigated a model of tunnel to be installed at the works of Sauter-Harle, Paris.

The dimensions of the model tested and the results of the tests made (experiments 35 to 39) are shown in the picture on top of Table V (a) and in Table V (a), respectively.

The value of $\rho_t$ as obtained from these experiments is more than twice the value of $\rho_t$ as obtained in the large Eiffel tunnel at Auteuil.

I have been present at the test of the final installation at the Sauter-Harlé works of the tunnel designed by Eiffel.

Due to a great limitation of available room the intake and outlet of the air could not take place into the open atmosphere.

The air circulation is established through a room right above the tunnel, and the prevailing conditions are not such as to insure a steady flow of the air into the experimental chamber of the tunnel.

In spite of all the unfavorable conditions under which the installation was made, the maximum velocity attained by the air in the cylindrical section of the tunnel is 190 feet per second with a 100 HP A.C. variable speed motor, 360 to 1200 R.P.M., driving a 6 blade airscrew. The value of $\rho_t$ corresponding to 100 HP and 190 feet second air velocity is 1.85 which is 35% larger than the value of $\rho_t$ as obtained with the Eiffel installation at Auteuil for a wind speed of 104 feet per second.

LOSSES IN A TUNNEL.

If no losses due to windage or to other causes were to be found in an aerodynamical tunnel having a diameter D at the entrance of the nozzle and at the outlet of the diffuser, and a diameter d at the cylindrical section, we would have:

$$\rho_b = \left(\frac{D}{d}\right)^4$$

If $\frac{D}{d} = 2$ we would have: $\rho_b = 16$. Comparing this figure with the values of $\rho_b$ as obtained from Eiffel experiments, we can appreciate the magnitude of the losses.

In Fig. 6 are given a few formulae derived by Eiffel for calculating the losses in an aerodynamical tunnel (see "Note sur le calcul des coefficients d'utilisation des buses pour souffleries aerodynamiques systeme G Eiffel."). The coefficient of friction of the air on smooth surfaces: $K_b$ is calculated according to Fritzsche's formula which I have expressed graphically in Fig. 7.

Applying the formula given to two models tested by Eiffel (experiments 1 and 8) the calculated values of $\rho_b$ are: 4.97 and 3.68, respectively, instead of 4.08 and 3.57 as obtained from test.

In order to compare the results obtained by Costanzi to the results obtained by Eiffel I have calculated $\rho_b$ for the two models Nos. 21 and 24 experimented upon by Costanzi, by applying the Eiffel formula (see Table VI), and I have calculated the efficiency of the air-screw: $\rho_v = \frac{\rho_t}{\rho_b}$ for wind speeds in the cylindrical section of the tunnel between 20 and 82 feet per second.

I have plotted in Fig. 6 the values thus obtained and I have taken the curve shown in Fig. 6 as being the efficiency curve of the air-screw used by Costanzi and Castallazzi in all the experiments made.

With the values of $\rho_v$ thus obtained and the values of $\rho_t$ given in Table II and Table III the values of $\rho_b$ given in Table IV were calculated and the results plotted in Fig. 8. In the same way, the values of $\rho_b$ as obtained directly by Eiffel in his experiments, (see Table V) were plotted in Fig. 9.

We can see from Fig. 8 that for each model the general tendency is to have $\rho_b$ decreasing slightly as the velocity of the air increases. These results are contrary to the results of other experiments made by Eiffel and to the results obtained by applying the formula given by Fig. 6, according to which the values of $\rho_b$ increase slightly as the velocity of the air increases. Experience has shown that the efficiency of large tunnels is larger than the efficiency of the reduced size models used for experimental purposes.

Eiffel suggests that a value $\rho_t = 3.25$ can be anticipated for a well designed tunnel of large dimensions.


Fig. 1.

*Model of Tunnel #1.*
with Intake and Exhaust made out of two truncated cones (full lines picture) $\alpha_c=15°$; $\alpha_d=3°30'$; $d=11\frac{13}{16}''$; $D_c=D_d=2d$; $l_{(ch)}=\frac{2}{3}d$; $l=12d$.

*Model of Tunnel #2.*
with conic Intake and Exhaust (dotted lines picture) all dimensions same as #1 except $l=6\frac{2}{3}d$.

*Model of Building #1.*
$H=6d$, $W=5d$, $L=18\frac{1}{3}d$.

*Model of Building #2.*
$H=3\frac{1}{3}d$, $W=5\frac{2}{3}d$, $L=12d$.

*Model of Building #3.*
Same as #2, except $L=16d$.

*Note.*
The front end (Air Inlet), the rear end (Air Outlet) and the roof of each model of building can be taken off. A diaphragm can be placed inside of building #1 normal to the axis of the tunnel, all around the section having the diameter d, with a view of preventing the air from circulating from one end to the other inside of the building.

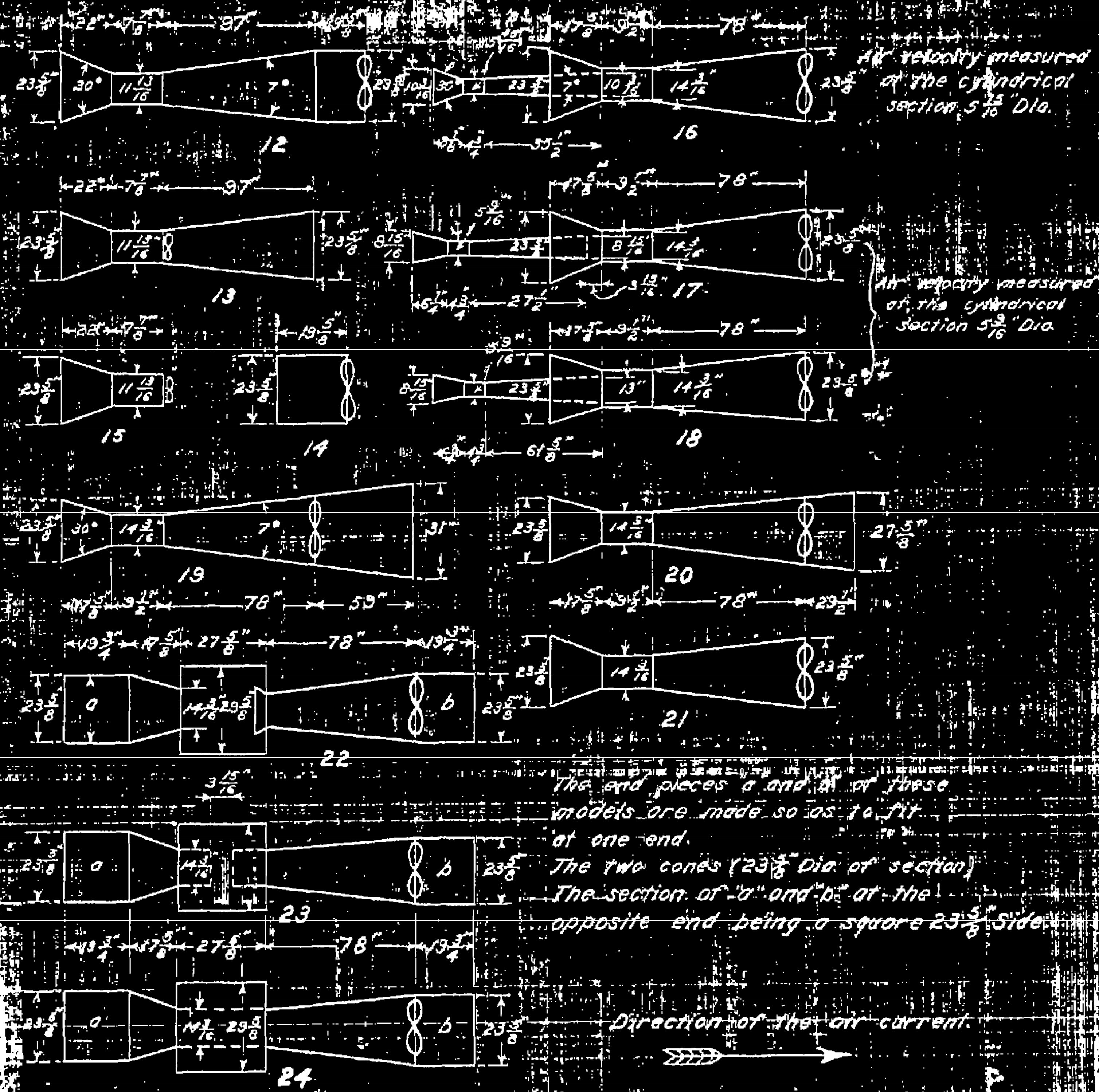
Values of $P_t=\frac{P_u}{P_m}$

| Experimental Conditions | Wind Velocity in Section "d." Ft. Per Sec. 20 | 33 | 53 | 66 | 82 | 100 | Serial no. of experiments |
|---|---|---|---|---|---|---|---|
| Tunnel #2, Building #2. Inlet and Outlet open. Roof closed. | .75 | .92 | 1.04 | .99 | 1.01 | | 1 |
| Tunnel #2. Building #2. Inlet closed, Outlet open. Roof closed. | .47 | .475 | .476 | .43 | .445 | | 2 |
| Tunnel #2, Building #2 Inlet open. Outlet closed. Roof closed. | .495 | .54 | .502 | .465 | .465 | | 3 |
| Tunnel #2, Building #2 Inlet and Outlet closed. Roof closed. | .457 | .51 | .47 | .445 | .46 | | 4 |
| Tunnel #2, Building #2. Inlet and Outlet closed. Roof open. | .42 | .48 | .485 | .52 | .5 | | 5 |
| Tunnel #2, Building #1. Inlet and Outlet closed. Roof open. | .43 | .52 | .57 | .57 | .54 | .55 | 6 |
| Tunnel #1, Building #1. Inlet and Outlet open. Roof closed. | 2.11 | 2.23 | 2.15 | 2.4 | 2.35 | 2.44 | 7 |
| Tunnel #1, Building #1. Inlet and Outlet closed. Roof closed. | .87 | 1.1 | 1.11 | 1.16 | 1.27 | 1.22 | 8 |
| Tunnel #1, Building #1, with Diaphragm. Inlet and Outlet open. Roof closed. | 1.74 | 2.02 | 2.25 | 2.45 | 2.65 | 2.68 | 9 |
| Tunnel #1, Building #3 Inlet and Outlet closed. Roof open. | .84 | .92 | .96 | .96 | 1.01 | .94 | 10 |
| Tunnel #1, Building #3. Inlet and Outlet open. Roof closed. | 1.2 | 1.77 | 2.1 | 2.15 | 2.25 | 2.37 | 11 |

Table I.

## INFLUENCE OF THE SURROUNDING BUILDING ON THE MECHANICAL EFFICIENCY OF AN AERODYNAMICAL TUNNEL OF THE EIFFEL TYPE.

Experiments made by Colonel Costanzi, Italian Army.




"Models of Tunnel Experimented Upon (Experimental results given in table II.)

By Colonel Costanzi, Italian Army.

Fig. 2.

Values of $\rho_t = \frac{\rho_u}{\rho_m}$

| Exper-im. Nº | Wind velocity in cylindrical section in ft. per sec. | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 6.5 | 13 | 20 | 26 | 33 | 38 | 40 | 50 | 53 | 66 | 82 | 100 | 128 |
| 12 | | | 1.5 | | 2.06 | | | | 2.2 | 2.2 | 2.23 | | |
| 13 | | | .89 | | 1.08 | | | | 1 | 1.25 | | | |
| 14 | .395 | .98 | 1.28 | 1.43 | 1.54 | | 1.48 | | | | | | |
| 15 | | | .56 | | .56 | | | | .535 | | | | |
| 16 | | | | | | | | .74 | | .9 | 1.01 | | |
| 17 | | | | | | .62 | | | | .8 | | .9 | .92 |
| 18 | | | .31 | | .36 | | | | .41 | .43 | .405 | | |
| 19 | | | 1.93 | | 2.34 | | | | 2.78 | 2.85 | 3. | | |
| 20 | | | 1.85 | | 2.2 | | | | 2.4 | 2.45 | 2.66 | | |
| 21 | | | 1.5 | | 1.3 | | | | 2.2 | 2.44 | 2.65 | | |
| 22 | | | 1.1 | | 1.27 | | | | 1.48 | 1.44 | 1.47 | | |
| 23 | | | 1.65 | | 2 | | | | 1.99 | 2.12 | 2.25 | | |
| 24 | | | 1.66 | | 2 | | | | 2.31 | 2.4 | 2.54 | | |

Table 2.

Influence of the design of an aerodynamical tunnel and location of the air-screw on the mechanical efficiency of the installation of a tunnel of the "Eiffel" type (see fig. 1.) Experiments made by Colonel Costanzi, Italian Army.

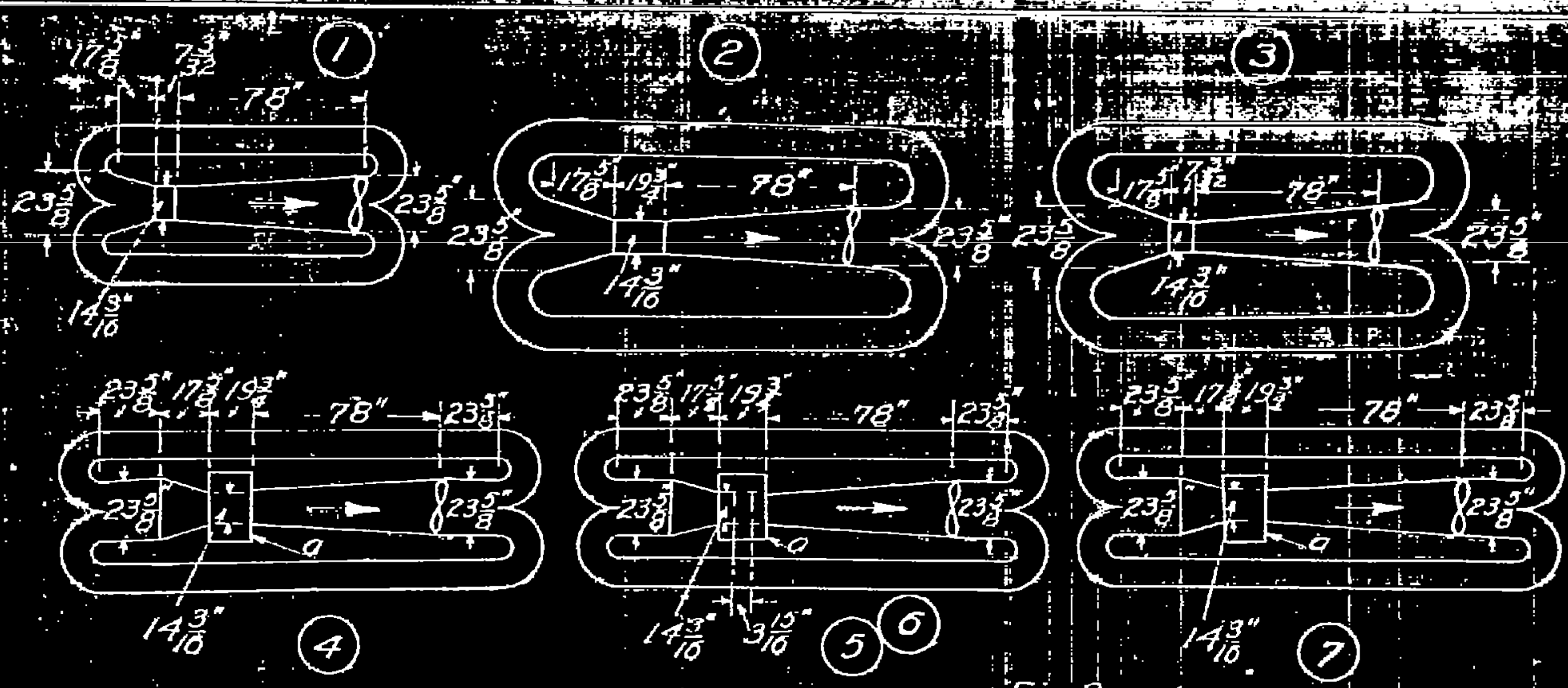



Fig. 3.

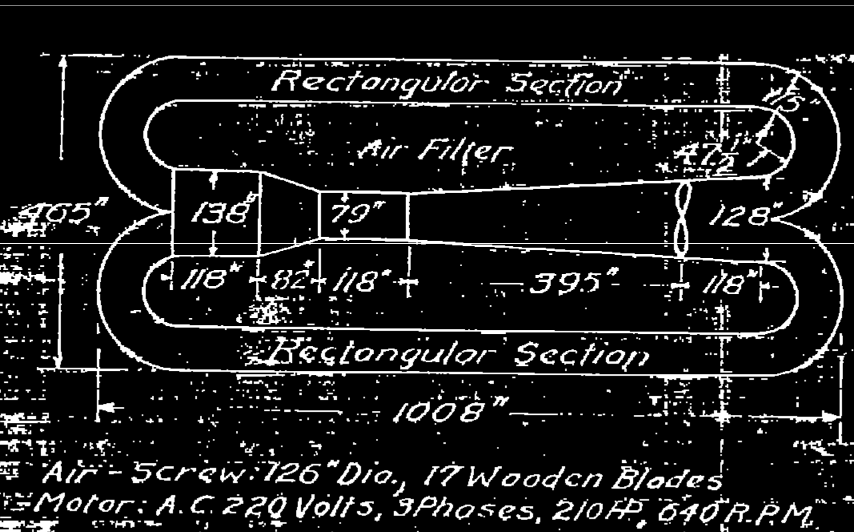
VALUES OF $P_t = \frac{P_u}{P_m}$

| EXPER. Nº | EXPERIMENTAL CONDITIONS | Wind Velocity in Section $14\frac{1}{8}$" Dia. Ft. per Sec. | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 20 | 26 | 33 | 50 | 53 | 66 | 75 | 82 | 98 | 100 |
| 1 | Ducts for the return of the air having a rectangular section not gradually recorded to the cones | 1.51 | | 2.06 | | 2.62 | 2.65 | | 2.94 | | 3.14 |
| 2 | Ducts for the return of the air having a circular section gradually recorded to the cones. | | 1.99 | 2.28 | | 2.62 | 2.85 | | 3.03 | 3.13 | |
| 3 | " " " | | 2.5 | 2.75 | | 3.22 | 3.6 | | 3.86 | 3.94 | |
| 4 | Ducts for the return of the air of a rectangular section gradually recorded to the cones - Door on cylinder "a" communicating to the outside, closed | | | 1.76 | 2.45 | | 2.55 | | 2.84 | 3.00 | |
| 5 | Ducts for the return of air same as #4 door on "a" communicating to the outside, closed. | 1.4 | | 1.64 | | 2.45 | 2.58 | | 2.66 | | |
| 6 | Same as #5 except: door on "a" communicating to the outside, opened. | .93 | | 1.19 | | 1.35 | 1.38 | | 1.51 | | |
| 7 | Same as #4 - door on "a" communicating to the outside, closed. | | | | | | 1.38 | 1.51 | | | |

Table III.

INFLUENCE OF THE DESIGN ON THE MECHANICAL EFFICIENCY OF AN AERODYNAMICAL TUNNEL OF THE "CROCCO" TYPE.

CROCCO TUNNEL INSTALLED AT THE "ISTITUTO CENTRALE AERONAUTICO" - ROME, ITALY.




Air-Screw: 126" Dia., 17 Wooden Blades
Motor: A.C. 220 Volts, 3 Phases, 210 HP, 640 R.P.M.

Fig. 4.

| Wind Velocity in Sect. 79" Dia. Ft/Sec | Motor R.P.M. | Motor Power HP | $P_t = \frac{P_u}{P_m}$ | Efficiency of Air Screw $P_v$ | $P_b = \frac{P_u}{P_v}$ |
|---|---|---|---|---|---|
| 33 | 97 | – | – | – | – |
| 66 | 186 | 7 | 3 | .77 | 3.9 |
| 99 | 285 | 27 | 2.62 | .74 | 3.55 |
| 132 | 372 | 60 | 2.8 | .72 | 3.9 |
| 165 | 458 | 113 | 2.9 | .75 | 3.86 |

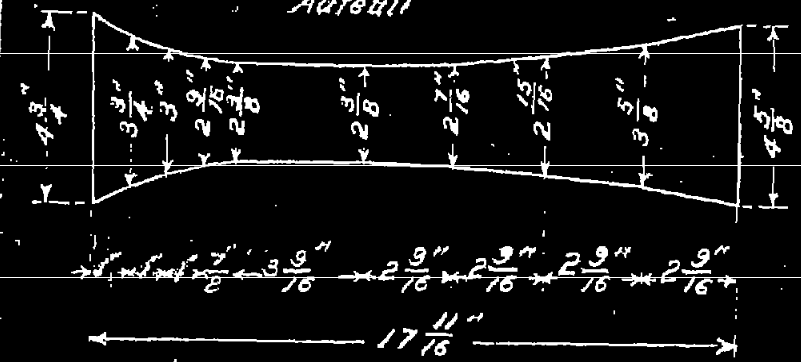
Table IV.

Experiments made by Lieut. Castellozzi, Italian Army.

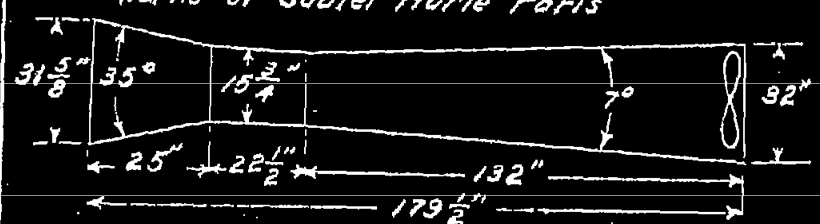
Figs. 3 & 4, Tables 3 & 4

5341-20

Model $\frac{1}{33.3}$ size of the Eiffel Tunnel at Auteuil




Model $\frac{1}{3}$ size of the tunnel installed at the works of Sauter Harle Paris




Experimental determination of $\rho_t$ on model of Sauter Harle Tunnel

| Experim. Nº | Wind Velocity Ft. per Sec. | $\rho_t = \frac{P_u}{P_m}$ | Experim. Nº | Wind Velocity Ft./Sec. | $\rho_t = \frac{P_u}{P_m}$ |
|---|---|---|---|---|---|
| 35 | 66 | 2.83 | 38 | 174 | 2.95 |
| 36 | 113 | 2.71 | 39 | 204 | 2.94 |
| 37 | 146 | 2.86 | | | |

Table 5(a).

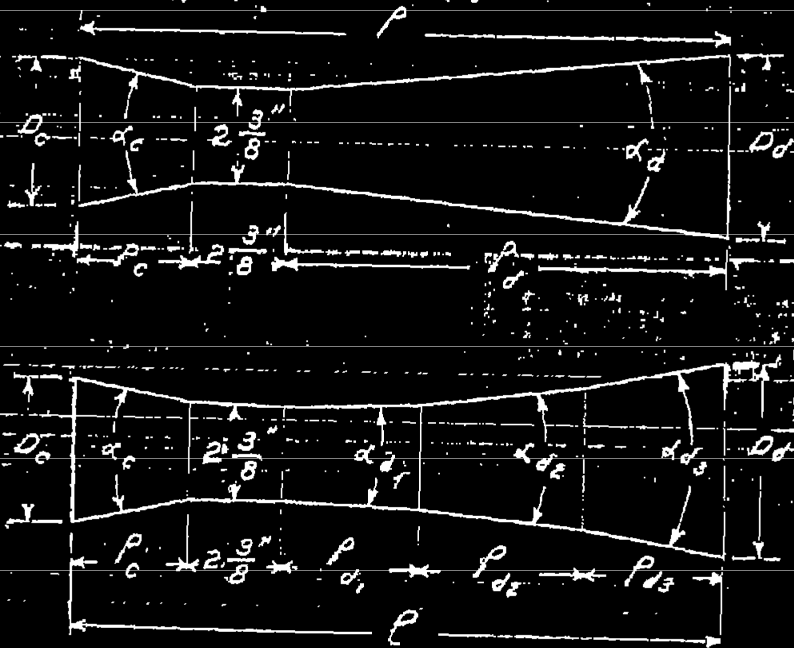



Fig. 5.

Experiments made by Eiffel.



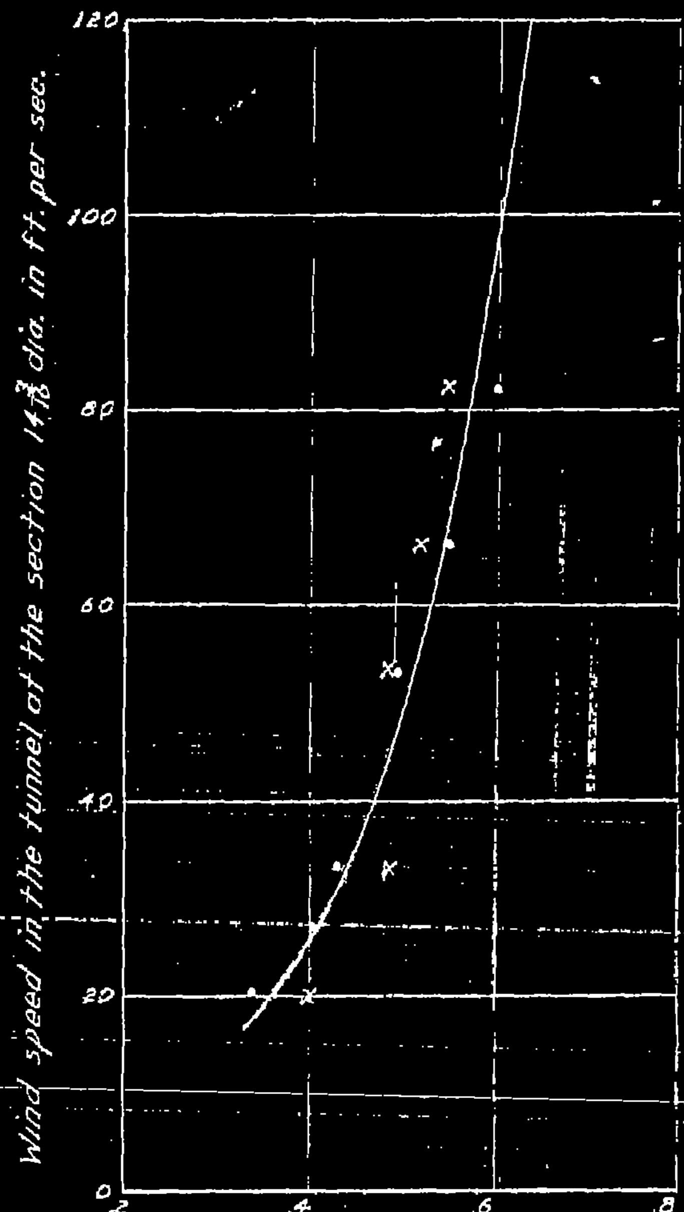
| Exper. Nº | $D_c$ | $\alpha_c$ | $b_c$ | $D_d$ | $\alpha_d$ | $b_d$ | $b$ | $\alpha_{d_1}$ | $b_{d_1}$ | $\alpha_{d_2}$ | $b_{d_2}$ | $\alpha_{d_3}$ | $b_{d_3}$ | Wind Speed Ft/Sec. | $\rho_b = \frac{h}{H}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 4 3/4" | 22° | 6" | 4 3/4" | 7° | 19 1/2" | 27 7/8" | — | — | — | — | — | — | | |
| 2 | " | " | " | 7 1/8" | " | 39" | 47 3/8" | — | — | — | — | — | — | 188 | 4.08 |
| 3 | " | " | " | 4 3/4" | 15° | 9" | 17 3/8" | — | — | — | — | — | — | 220 | 5.54 |
| 4 | " | " | " | 7 1/8" | " | 18" | 26 3/8" | — | — | — | — | — | — | 162 | 3 |
| 5 | 7 7/8" | " | 12 | 4 3/4" | 7° | 19 1/2" | 33 7/8" | — | — | — | — | — | — | 170 | 3.33 |
| 6 | " | " | " | 7 1/8" | " | 39" | 53 3/8" | — | — | — | — | — | — | 197 | 4.48 |
| 7 | " | " | " | 4 3/4" | 15° | 9" | 23 3/8" | — | — | — | — | — | — | 218 | 5.45 |
| 8 | " | " | " | 7 1/8" | " | 18" | 32 3/8" | — | — | — | — | — | — | 165 | 3.10 |
| 9 | 4 3/4" | 25° | 4 7/8" | 4 3/4" | " | 9" | 16 1/4" | — | — | — | — | — | — | 177 | 3.57 |
| 10 | " | " | " | 7 1/8" | " | 18" | 25 1/4 | — | — | — | — | — | — | 160 | 2.93 |
| 11 | " | " | " | 4 3/4" | — | — | 18 9/16" | 7° | 3 15/16" | 14° | 7 3/8" | — | — | 167 | 3.2 |
| 12 | " | " | " | 7 1/8" | — | — | 24 15/16" | " | " | " | " | 21° | 6 3/8" | 154 | 2.7 |
| 13 | 7 7/8" | " | 10 5/8" | 4 3/4" | 15° | 9" | 22" | — | — | — | — | — | — | 157 | 2.82 |
| 14 | " | " | " | 7 1/8" | " | 18" | 31" | — | — | — | — | — | — | 165 | 3.12 |
| 15 | " | " | " | 4 3/4" | — | — | 24 5/16" | 7° | 3 15/16" | 14° | 7 3/8" | — | — | 178 | 3.62 |
| 16 | " | " | " | 7 1/8" | — | — | 30 11/16" | " | " | " | " | 21° | 6 3/8" | 161 | 2.96 |
| 17 | 4 3/4" | 35° | 3 7/16" | 4 3/4" | 7° | 19 1/2" | 25 5/16" | — | — | — | — | — | — | 166 | 3.16 |
| 18 | " | " | " | " | 15° | 9" | 14 13/16" | — | — | — | — | — | — | 189 | 4.09 |
| 19 | " | " | " | 7 1/8" | " | 18" | 23 13/16" | — | — | — | — | — | — | 156 | 2.77 |
| 20 | " | " | " | 4 3/4" | 22° | 6" | 11 13/16" | — | — | — | — | — | — | 169 | 3.26 |
| 21 | " | " | " | 7 1/8" | " | 12 1/2 | 17 15/16" | — | — | — | — | — | — | 114 | 1.48 |
| 22 | " | " | " | 4 3/4" | — | — | 17 1/8" | 7° | 3 15/16" | 14° | 7 3/8" | — | — | 125 | 1.79 |
| 23 | " | " | " | 7 1/8" | — | — | 23 1/2" | " | " | " | " | 21° | 6 3/8" | 152 | 2.68 |
| 24 | 7 7/8" | " | 7 1/2" | 4 3/4" | 7° | 19 1/2" | 29 3/8" | — | — | — | — | — | — | 157 | 2.84 |
| 25 | " | " | " | 7 1/8" | " | 39" | 48 7/8" | — | — | — | — | — | — | 195 | 4.38 |
| 26 | " | " | " | 4 3/4" | 15° | 9" | 18 7/8" | — | — | — | — | — | — | 223 | 5.67 |
| 27 | " | " | " | 7 1/8" | " | 18" | 27 7/8" | — | — | — | — | — | — | 166 | 3.11 |
| 28 | " | " | " | 4 3/4" | — | — | 21 3/16" | 7° | 3 15/16" | 14° | 7 3/8" | — | — | 176 | 3.53 |
| 29 | " | " | " | 7 1/8" | — | — | 27 9/16" | " | " | " | " | 21° | 6 3/8" | 162 | 2.99 |
| 30 | " | 45° | 5 3/4" | 4 3/4" | 15° | 9" | 17 1/8" | — | — | — | — | — | — | 158 | 2.91 |
| 31 | " | " | " | 7 1/8" | " | 18" | 26 1/8" | — | — | — | — | — | — | 164 | 3.1 |
| 32 | " | " | " | 4 3/4" | — | — | 19 7/16" | 7° | 3 15/16" | 14° | 7 3/8" | — | — | 174 | 3.48 |
| 33 | " | " | " | 7 1/8" | — | — | 25 13/16" | " | " | " | " | 21° | 6 3/8" | 152 | 2.68 |
| 34 | Model of the Eiffel Tunnel at Auteuil | | | | | | | | | | | | | 162 | 3.5 |
| | | | | | | | | | | | | | | 148 | 2.5 |

Table 5.

Fig. 8. Table. 5.

Fig. 6.

• Experiment #21 (Costanzi).
× " #24 "




$p_v = \frac{p_t}{p_b}$ = Efficiency of air screw.

(Values of $p_t$ calculated from test (see table II)
Values of $p_b$ calculated by using the formulae given by Eiffel).

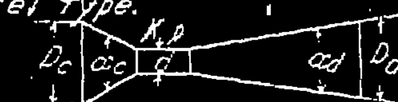
Table 6.

| | Wind speed in tunnel at the section $14\frac{3}{16}$ dia., ft. per sec. | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Experiment #21 (Costanzi). | | | | | Experiment #24 (Costanzi). | | | | |
| | 20 | 33 | 53 | 66 | 82 | 20 | 33 | 53 | 66 | 82 |
| Pc | 00755 | .007 | .0065 | .0063 | .0061 | 00755 | .007 | .0065 | .0063 | .0061 |
| Pch | 01195 | .011 | 0103 | .01 | .0097 | .035 | 0323 | .03 | .029 | .0283 |
| $P^{p}_{d}$ | .032 | .0296 | .0276 | .0265 | .026 | .032 | .0296 | .0276 | .0265 | .026 |
| Pd | .0495 | .0495 | .0495 | .0495 | .0495 | .0495 | .0495 | .0495 | .0495 | .0495 |
| Ppu | ·13 | ·13 | ·13 | ·13 | ·13 | ·13 | ·13 | ·13 | ·13 | ·13 |
| $P_b$ = Total | ·231 | ·2271 | ·2239 | ·2223 | ·2213 | ·25405 | ·2484 | ·2436 | ·2413 | ·2399 |

Calculated values of $P_b$.

$\rho_b = \frac{1}{P_b}$.

Formulae given by Eiffel for calculating the losses in a tunnel of the Eiffel type.




$n_c = \left(\frac{D_c}{d}\right)^2$; $n_d = \left(\frac{D_d}{d}\right)^2$; $m = \frac{l}{d}$

$K_f$ = Coefficient of friction of the air (Fritzsche's formulae) see fig. 7.

$P_c = \frac{8k_f}{\sin\frac{\alpha_c}{2}} \times \frac{n_c^2 - 1}{n_c^2}$ (Losses in the entrance nozzle.).

$P_{ch} = 64\,K_f\,m$ (Losses in the Experimental Chamber.).

$P^{p}_{d} = \frac{8k_f}{\sin\frac{\alpha_d}{2}} \times \frac{n_d^2 - 1}{n_d^2}$ (Diffuser losses due to friction.).

$P_d = \left(\frac{n_d - 1}{n_d}\right)^2 \sin\alpha_d$ (Diffuser losses due to the enlargement of the section.).

$P_f = \frac{1}{n_d^2}$ = (Energy losses at the outlet of the diffuser).

$P_b = \frac{1}{P_c + P_{ch} + P^{p}_{d} + P_d + P_f}$ (Efficiency of the tunnel.).

Note:— In a closed type of tunnel (like the Crocco tunnel): $P_f = 0$ but in addition, the following losses must be calculated:

$P_2 = \frac{64\,K_f\,m_1}{n_d^2}$ (losses in the air return duct); $P_{cd} = \frac{.13 + .16\left(\frac{D_d}{\rho}\right)^{2}}{n_d^2}$ (losses in a bend) where: $m_1 = \frac{\text{length of air return duct}}{D_d}$; $n$ = radius of bend of the return duct (measured at the axis of the bend).

Fig. 6. Table 6.

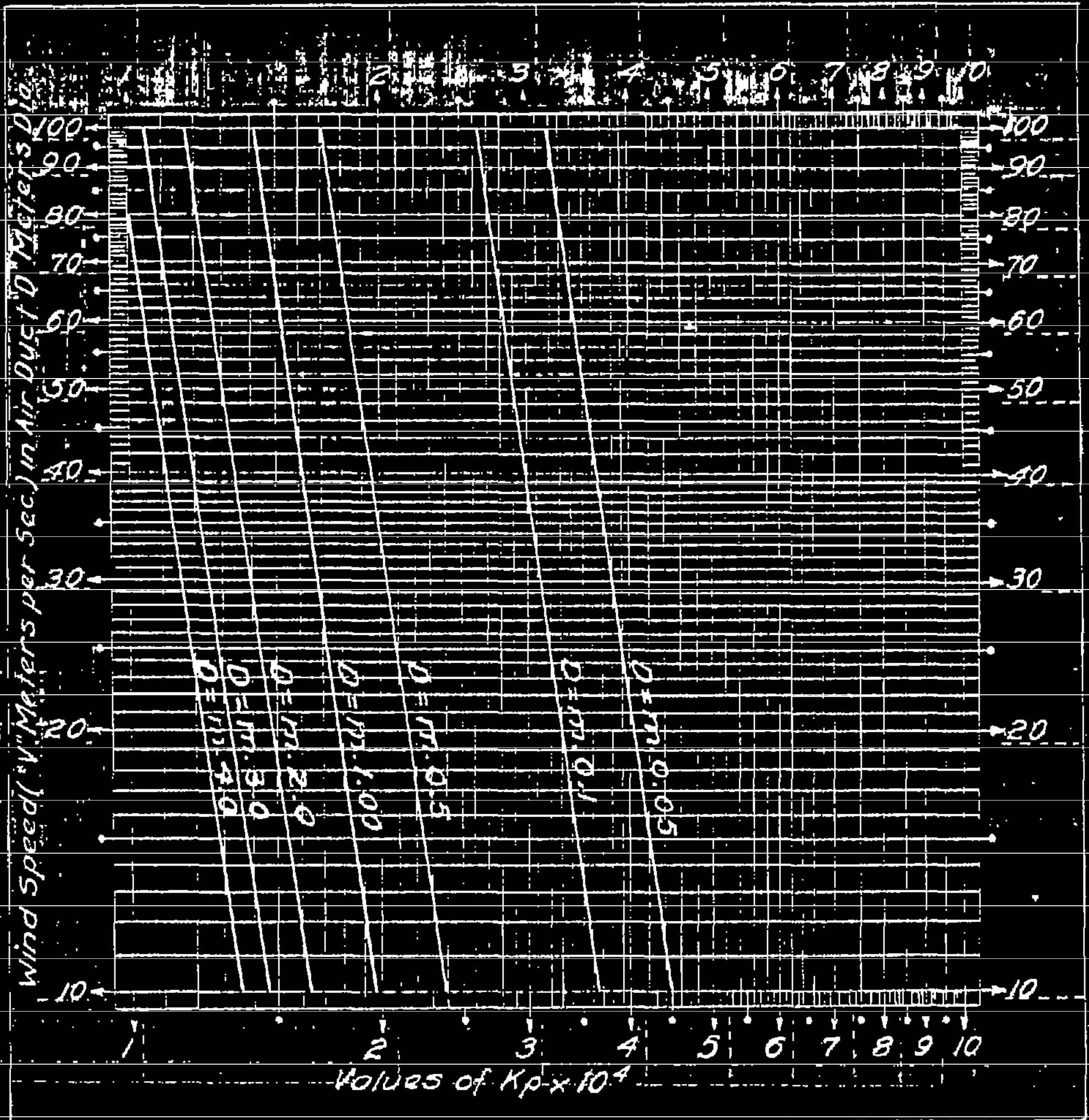



Fig. 7. FRITZSCHE'S FORMULA:

$$K_p = \frac{2.79}{10^4} \times D^{-0.269} \times V^{-0.148}$$

$K_p$ = Coefficient of Air Friction.
D = Dia. of Air Duct (In the case of an Aerodynamical Tunnel, "D" is the Dia. of the Experimental Chamber) in Meters.
V = Velocity of the Air in Duct having the Dia. "D" in meters per second.
Note:- The Values of $K_p$ given above are for an Air Temp. of 15° and a Pressure of 30" and for Air Ducts with smooth surfaces.

VALUES OF $\rho = \frac{P_u}{P_m}$ AND R.P.M. OF MOTOR.

| Air-Screw tested in Model of Tunnel #4 (See table III) Diameter = $23\frac{5}{8}$" | Wind Velocity in Sect. $14\frac{1}{8}$" Dia. Ft/Sec | | | | | |
|---|---|---|---|---|---|---|
| | 20 | 33 | 53 | 66 | 82 | 98 |
| 24 Blades of Uniform Width: $1\frac{1}{4}$" $\frac{Width}{Dia.}$ = .0435 | .95 (292) | 1.68 (449) | 2.1 (700) | 2.45 (840) | 2.57 (1035) | 2.65 (1230) |
| 24 Blades of Uniform Width: $\frac{45}{64}$" $\frac{Width}{Dia.}$ = .03 | 1.01 (316) | 1.4 (515) | 1.82 (770) | 2.00 (940) | 2.1 (1150) | 2.18 (1370) |
| 16 Blades of Uniform Width: $1\frac{17}{32}$" $\frac{Width}{Dia.}$ = .065 | 1.25 (270) | 1.85 (434) | 2.22 (665) | 2.30 (813) | 2.5 (1000) | 2.55 (1120) |
| 12 Blades of Uniform Width: $1\frac{1}{32}$" $\frac{Width}{Dia.}$ = .0435 | .96 (337) | 1.55 (535) | 2.01 (820) | 2.18 (1010) | 2.36 (1230) | 2.42 (1470) |
| 8 Blades of Uniform Width: $1\frac{17}{32}$" $\frac{Width}{Dia.}$ = .065 | 1.24 (304) | 1.78 (500) | 2.27 (760) | 2.4 (945) | 2.56 (1160) | 2.57 (1395) |
| 6 Blades of Uniform Width: $1\frac{17}{32}$" $\frac{Width}{Dia.}$ = .065 | 1.16 (342) | 1.65 (570) | 2.00 (892) | 2.15 (1100) | 2.35 (1330) | 2.37 (1590) |
| 6 Blades "CROISSANT" Type. | 1.45 (328) | 1.83 (515) | 1.91 (820) | 2.01 (1010) | 2.09 (1240) | 2.1 (1480) |
| 16 Blades "N.P.L." Type. | 1.6 (337) | 1.9 (550) | 2.13 (850) | 2.29 (1050) | 2.3 (1310) | 2.38 (1555) |

Table 7.

INFLUENCE OF THE DESIGN OF THE AIR-SCREW ON THE MECHANICAL EFFICIENCY OF MODEL #4 (SEE TABLE III) OF THE "CROCCO" TUNNEL.

Figures between ( ) are the R.P.M. of the Driving Motor for any corresponding wind velocity in the section of the Tunnel $14\frac{1}{8}$" Dia.

Experiments made by LIEUT. CASTELLAZZI, ITALIAN ARMY.

5341-26

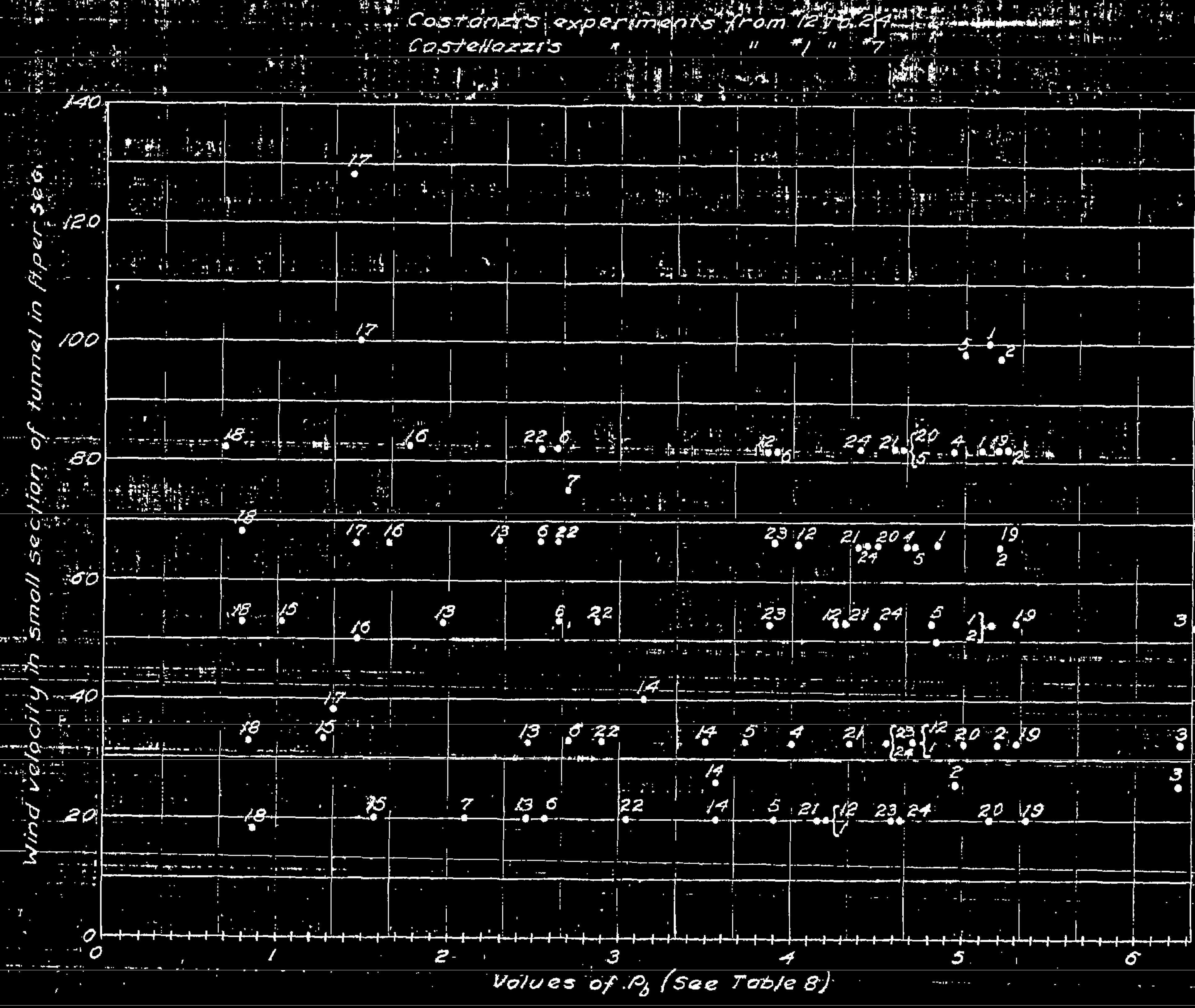

Costanzi's experiments from 12 to 24
Castellazzi's " " 1 " 7
Wind velocity in small section of tunnel in ft. per sec.
Values of $P_b$ (See Table 8)
0
20
40
60
80
100
120
140
1
2
3
4
5
6

Fig. 8

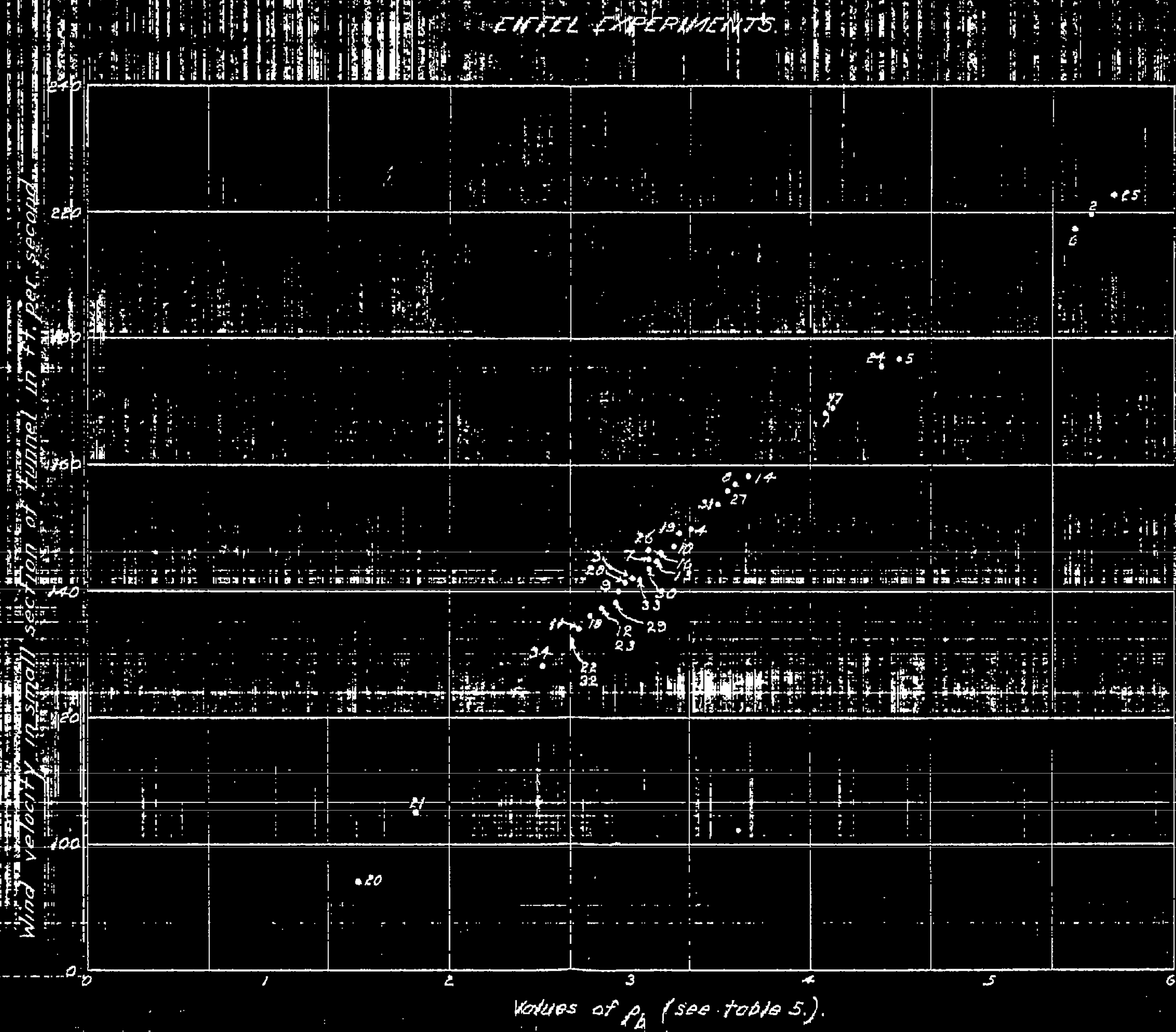
## CALCULATED VALUES OF $\rho_b = \frac{\rho_b}{\rho_v}$

(Values of $\rho_t$ from tables II & III; Values of $\rho_v$ from Fig. 6.)

| EXPERIMENTER'S NAME | EXPER. Nº | Wind Velocity in small Section of Tunnel in Ft. per Sec. | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 20 | 26 | 33 | 38 | 40 | 50 | 53 | 66 | 75 | 82 | 98 | 100 | 128 |
| COSTANZI | 12 | 4.2 | | 4.7 | | | | 4.27 | 4.02 | | 3.85 | | | |
| " | 13 | 2.48 | | 2.45 | | | | 1.94 | 2.3 | | | | | |
| " | 14 | 3.56 | 3.57 | 3.5 | | 3.15 | | | | | | | | |
| " | 15 | 1.56 | | 1.27 | | | | 1.04 | | | | | | |
| " | 16 | | | | | | 1.46 | | 1.65 | | 1.76 | | | |
| " | 17 | | | | 1.32 | | | | 1.46 | | | | 1.48 | 1.44 |
| " | 18 | .86 | | .82 | | | | .8 | .79 | | .7 | | | |
| " | 19 | 5.35 | | 5.3 | | | | 5.4 | 5.2 | | 5.2 | | | |
| " | 20 | 5.15 | | 5 | | | | 4.65 | 4.5 | | 4.62 | | | |
| " | 21 | 4.18 | | 4.32 | | | | 4.3 | 4.45 | | 4.6 | | | |
| " | 22 | 3.05 | | 2.9 | | | | 2.88 | 2.62 | | 2.55 | | | |
| " | 23 | 4.6 | | 4.55 | | | | 3.87 | 3.88 | | 3.9 | | | |
| " | 24 | 4.62 | | 4.55 | | | | 4.5 | 4.4 | | 4.4 | | | |
| CASTELLAZZI | 1 | 4.2 | | 4.7 | | | | 5.15 | 4.85 | | 5.1 | | 5.15 | |
| " | 2 | | 4.97 | 5.2 | | | | 5.15 | 5.2 | | 5.25 | 5.2 | | |
| " | 3 | | 6.25 | 6.25 | | | | 6.35 | 6.6 | | 6.7 | 6.52 | | |
| " | 4 | | | 4 | | | 4.85 | | 4.65 | | 4.92 | 5 | | |
| " | 5 | 3.9 | | 3.73 | | | | 4.8 | 4.7 | | 4.62 | | | |
| " | 6 | 2.58 | | 2.7 | | | | 2.65 | 2.52 | | 2.62 | | | |
| " | 7 | 2.09 | | | | | | | | 2.7 | | | | |

Table 5

5341-26


EIFFEL EXPERIMENTS.
Wind velocity in small section of tunnel in ft per second
Values of $\rho_b$ (see table 5.)
240
220
200
180
160
140
120
100
0
0
1
2
3
4
5
6
25
2
6
24
5
17
8
14
27
31
19
4
26
10
7
13
3
28
30
9
33
11
18
12
29
23
34
22
32
21
20